



EXOHOST

Modern Instrumentation for Astronomical Spectroscopy

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Part I: Spectrometers

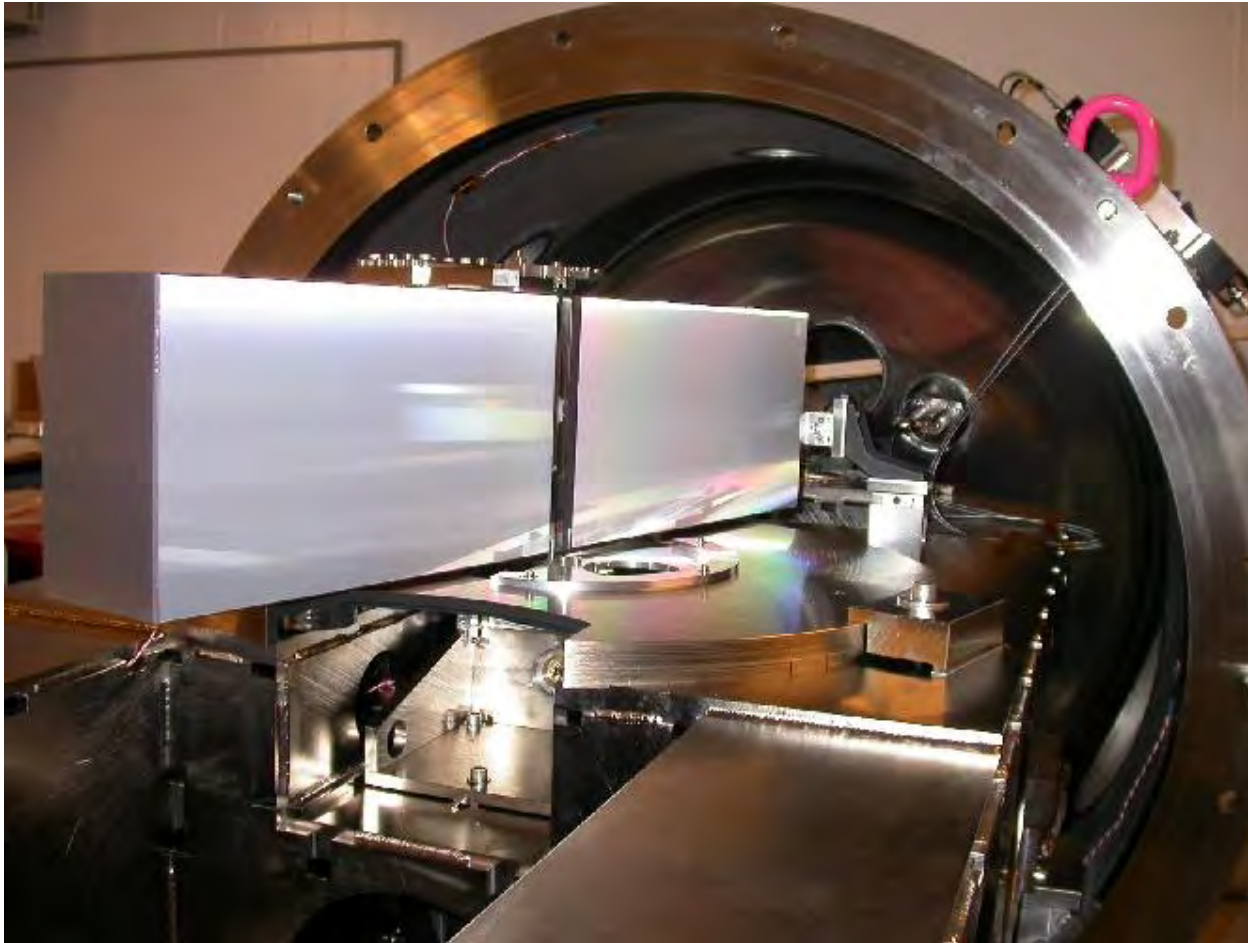
Classification of astronomical spectrometers

- By spectral coverage
- By spectral resolution
- By multiplexity
- By combining spectral and spatial information

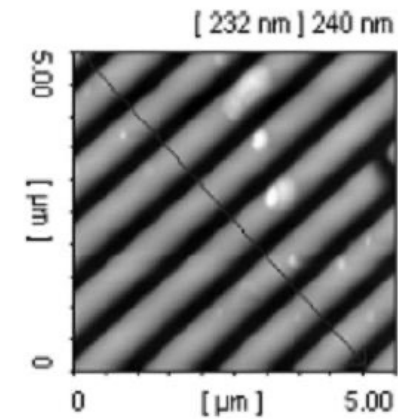
Resolution

- Spectral resolving power is defined as $R = \lambda / \Delta\lambda$.
This is a good quantity for grating-based instruments as R is approximately constant across the spectral range.
- Low resolution is $R < 1000$.
- Medium resolution $1000 < R < 20000$.
- High resolution $R > 20000$.
- Low resolution can be an objective prism or a tunable filter. In both cases R is a strong function of wavelength but people still use R .

High-resolution spectrometry uses diffraction grating



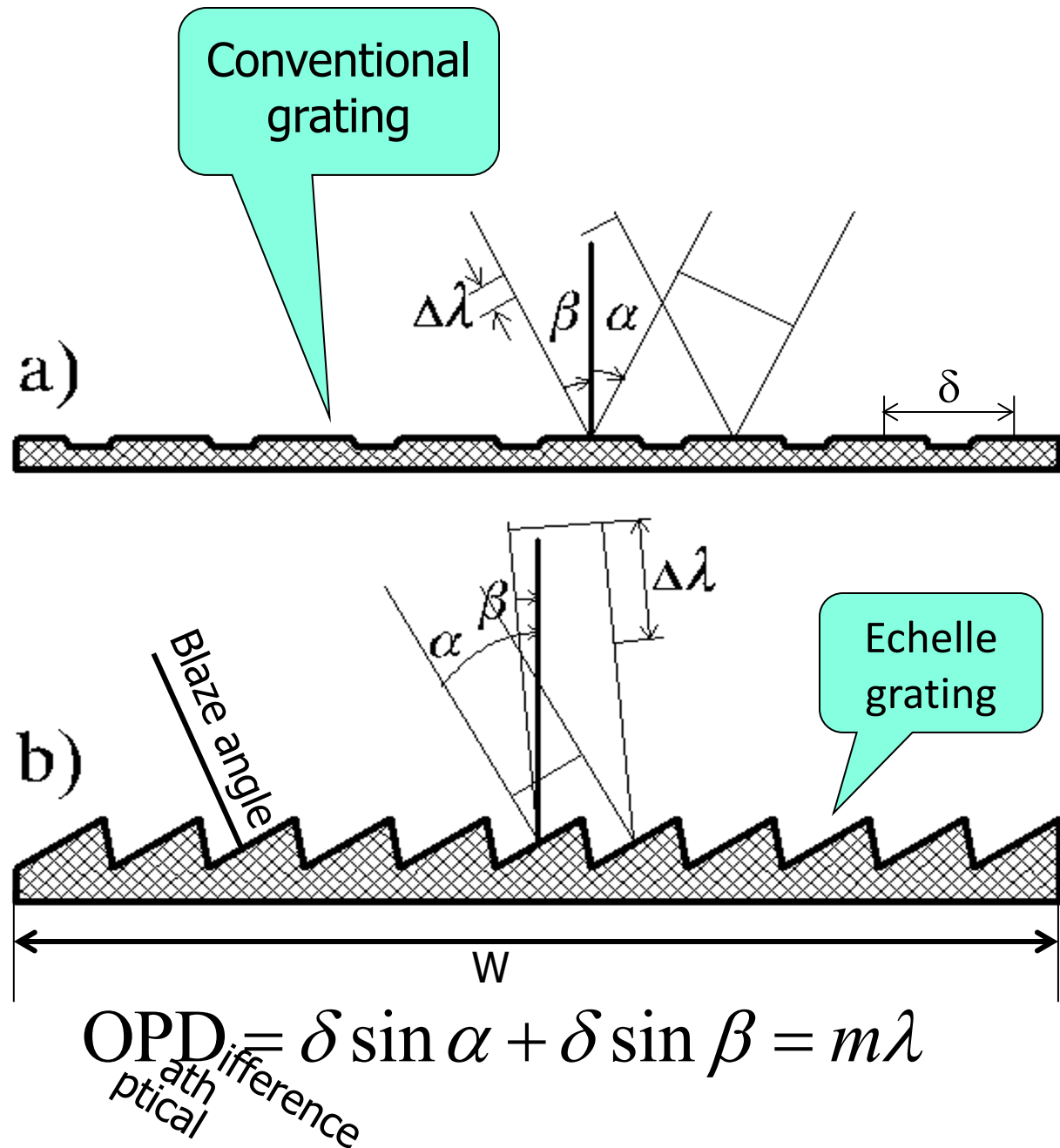
ESO HARPS spectrometer uses two echelle gratings aligned to a few nanometers



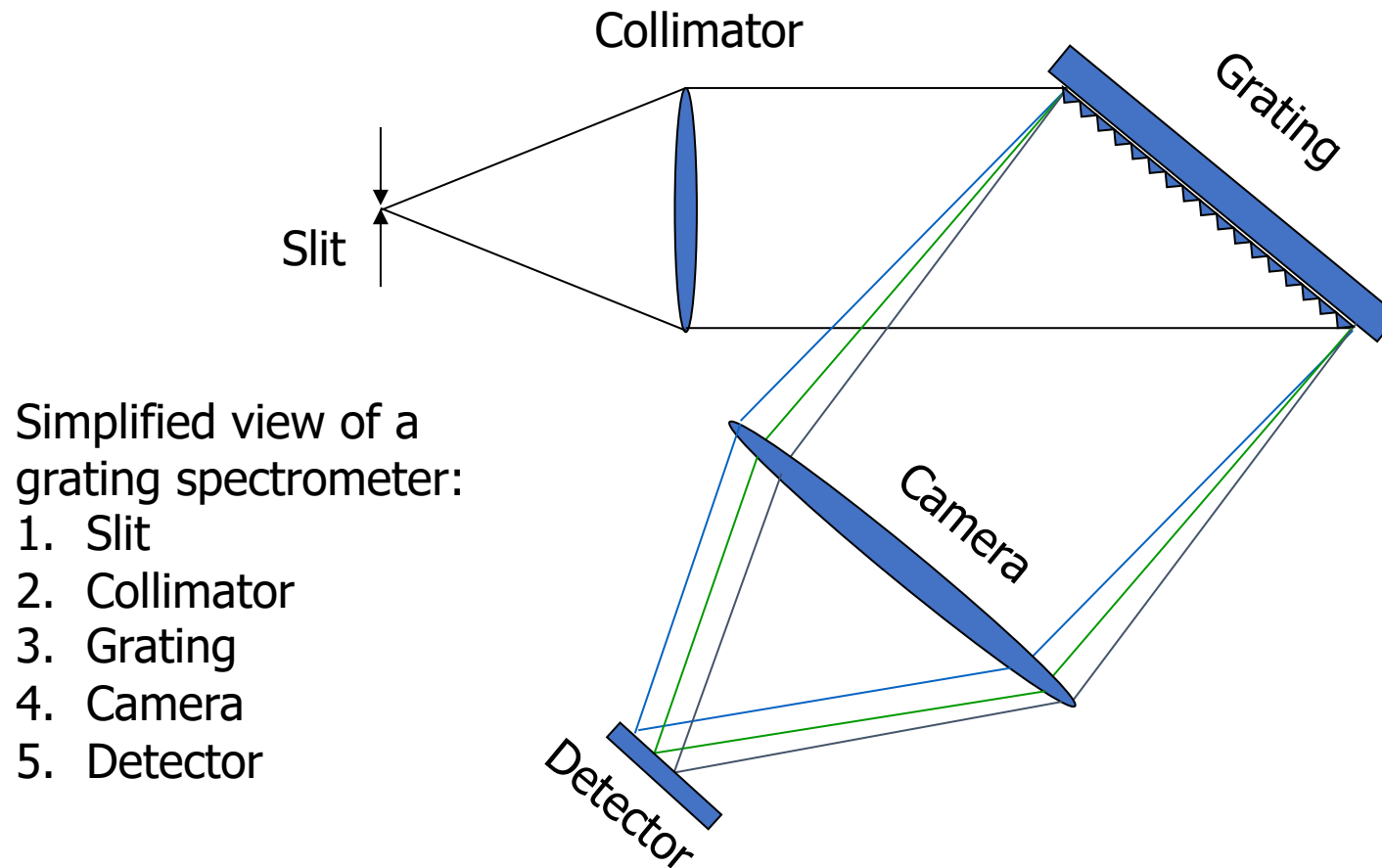
Gratings

Interference
between
grooves

Grating formula:



Grating spectrometer is an imaging system



A bit of math:

- Expression for angular dispersion is found by differentiating the grating equation, assuming constant incidence angle:

$$m d \lambda = \delta \cos \beta d \beta$$

$$\frac{d \lambda}{d \beta} = \delta \cos \beta / m \quad \text{Angular dispersion}$$

- Angular size of the slit image:

$$\Delta \alpha \cos \alpha = s / f_{\text{coll}} \cos \alpha = -\Delta \beta \cos \beta$$

$$|\Delta \beta| = \frac{s \cdot \cos \alpha}{f_{\text{coll}} \cdot \cos \beta}$$

...and a bit more:

- Combining the expression of the slit image size and the angular dispersion we get the expression for the resolution element:

$$m\Delta\lambda = \frac{s}{f_{\text{coll}}} \cdot \delta \cos \alpha$$

while the wavelength is given by the grating equation:

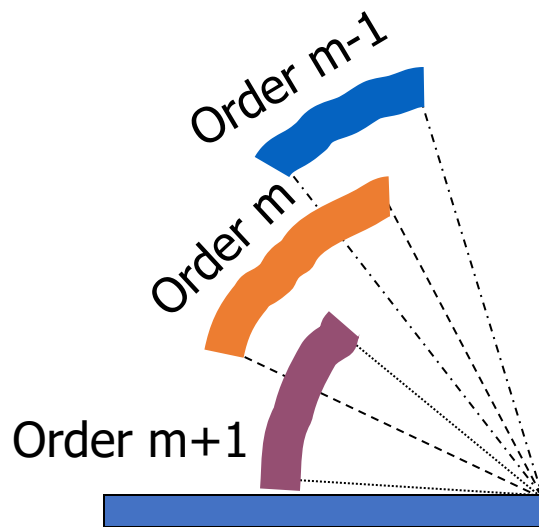
$$m\lambda = \delta (\sin \alpha + \sin \beta)$$

- Dividing the 2nd by the 1st gives the expression for R:

$$R = \frac{\lambda}{\delta\lambda} = \frac{f_{\text{coll}}}{s} \frac{\sin \alpha + \sin \beta}{\cos \alpha}$$

Free spectral range

Free spectral range (FSR) of a diffraction grating is defined as the difference between two wavelengths reflected in the same direction β in two adjacent orders.


$$\begin{aligned}\text{FSR} &= \lambda_m - \lambda_{m+1} = \frac{\delta \sin \beta}{m} - \frac{\delta \sin \beta}{m+1} = \\ &= \frac{\delta \sin \beta}{m \cdot (m+1)}\end{aligned}$$

For a prism FSR is the whole spectral range!

Modern concepts

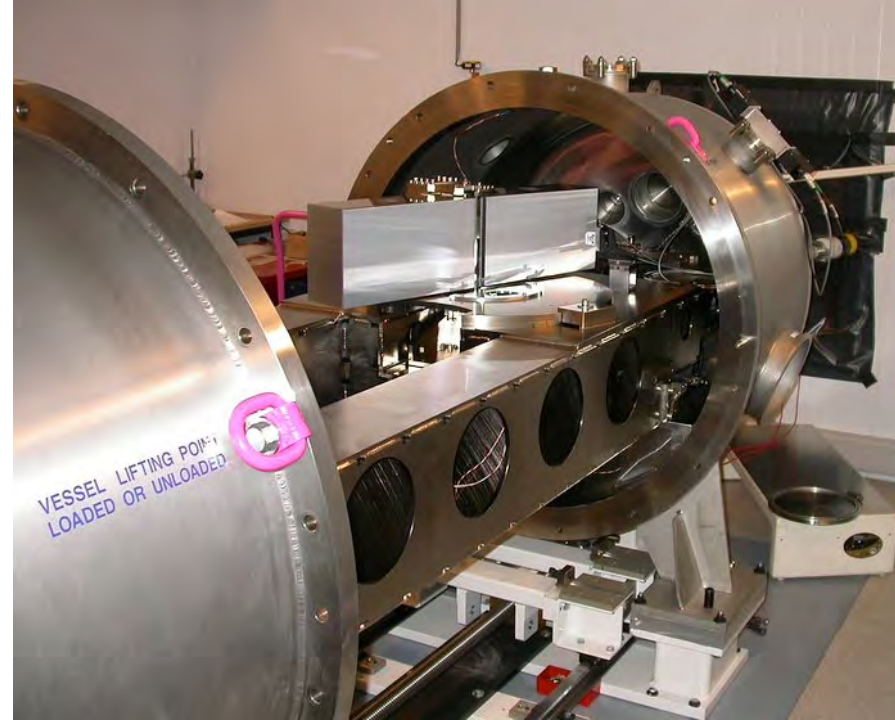
- Echelle gives high resolving power (high orders) and high efficiency (no dark stripes).
- Spectral orders overlap (maximum reflection is always at the blaze angle).
- This means that an order selection filter or a cross-disperser is needed (e.g. grating or prism).
- Central wavelength of an order m is given by:

$$\lambda_m = 2\delta \sin \theta_{\text{blaze}} / m$$

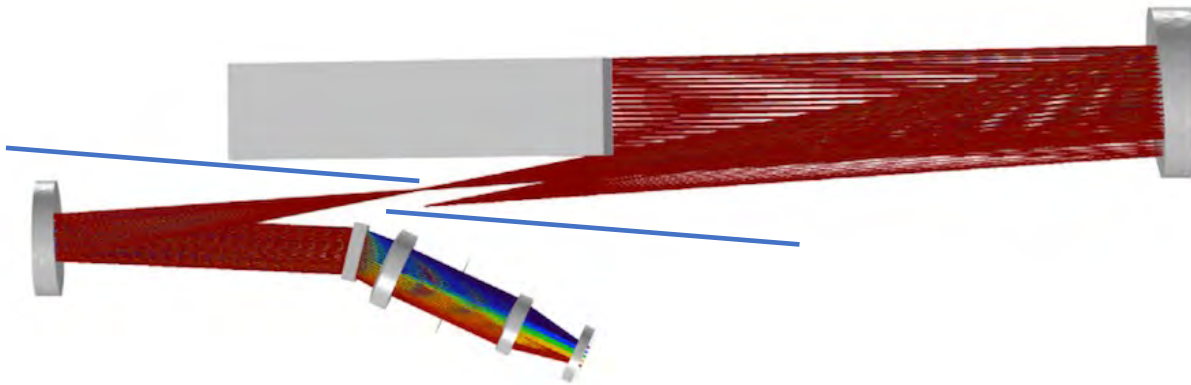
- With a cross-disperser the whole spectrum is packed in a rectangular 2D format, perfect for an electronic detector.

White pupil design

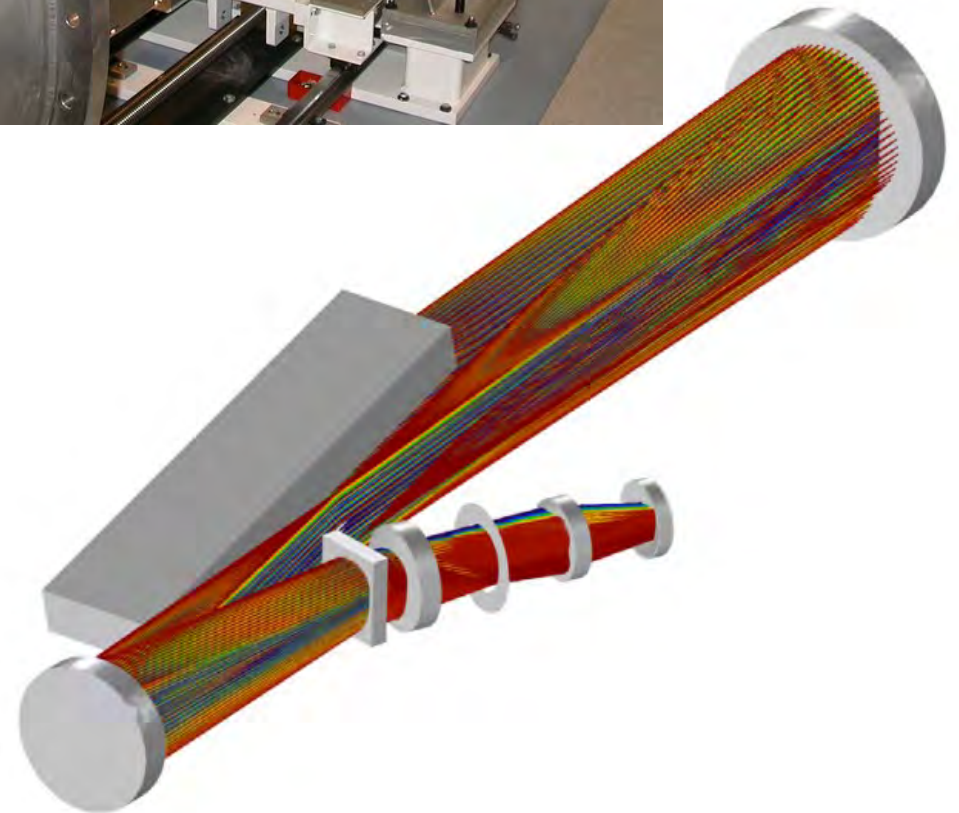
Two separate dispersions: echelle and cross.
Can be optimised separately.
Can be physical separated except for small whole.



HARPS 3.6m
Courtesy ESO

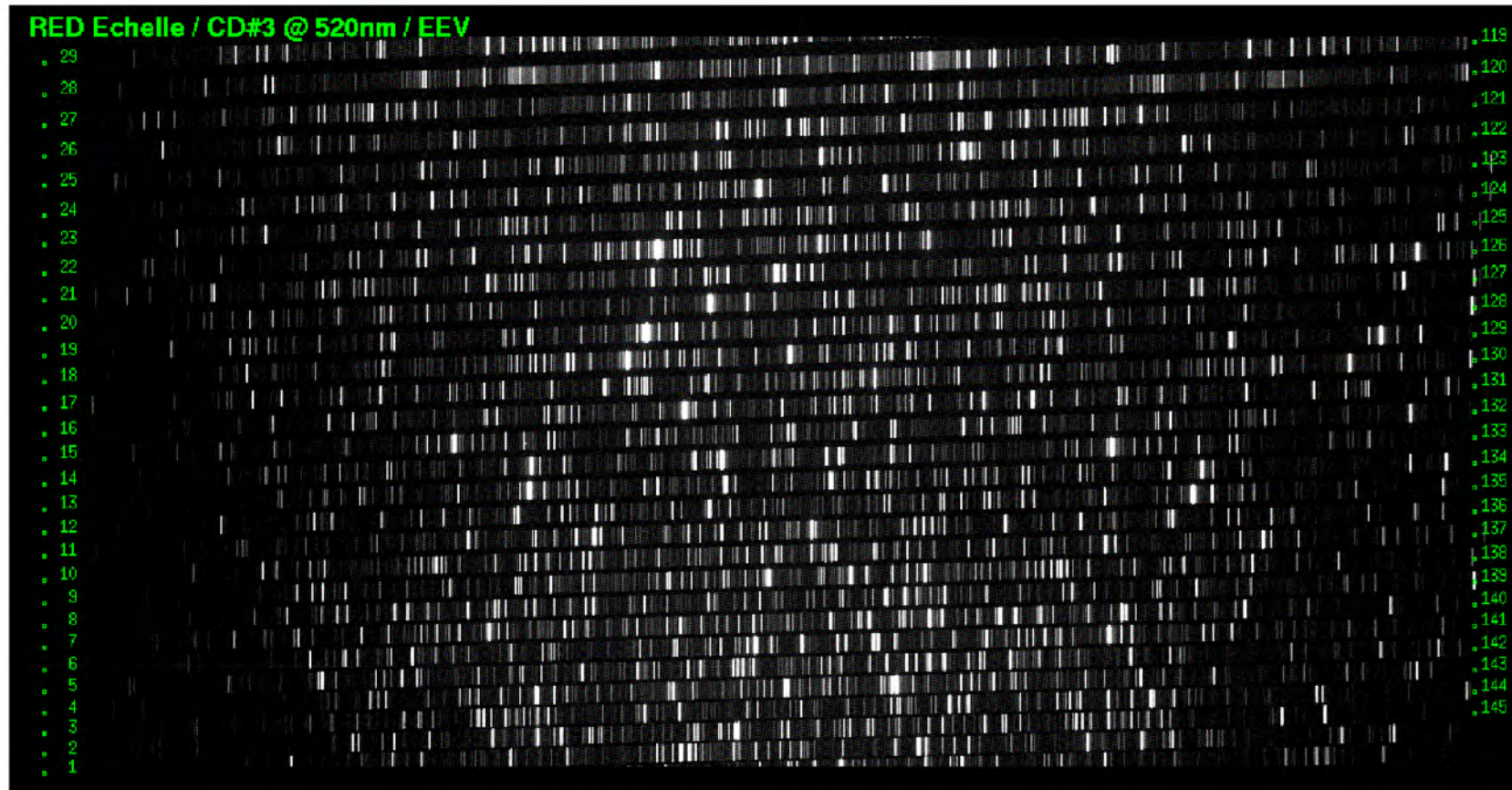


Courtesy Caty Fairclough at Comsol.com

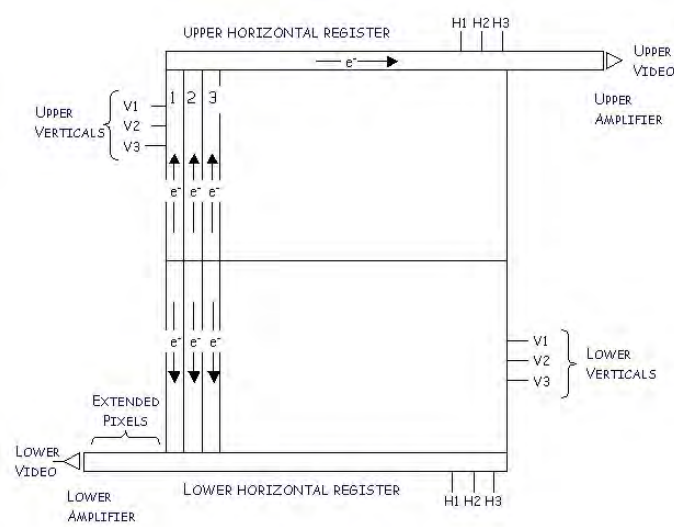


Echelle focal plane layout

Thorium Argon emission line spectrum

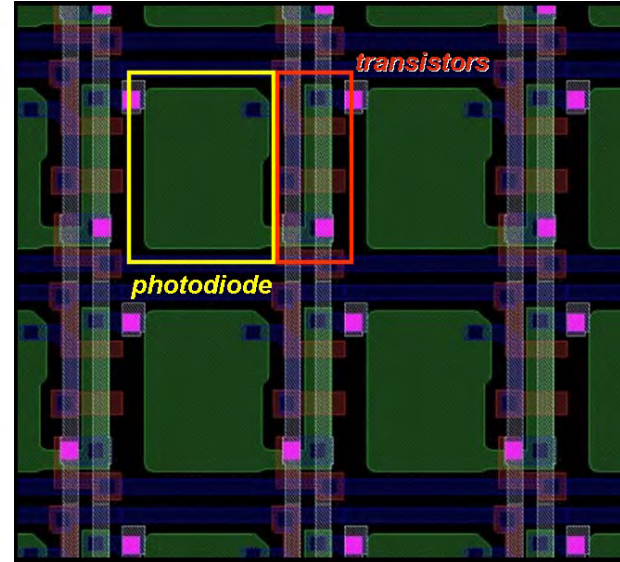


Part II: Detectors



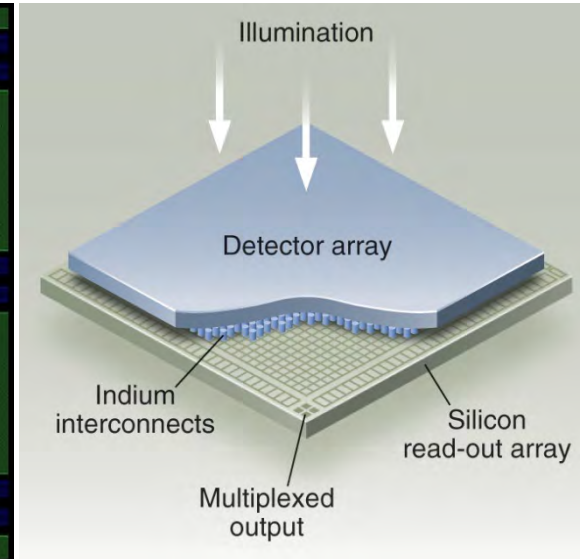
CCD

Charge-coupled
device



Monolithic CMOS

Complementary
Metal Oxide
Semiconductor



Hybrid CMOS

HgCdTe
Visible through IR

Silicon - Visible through near IR

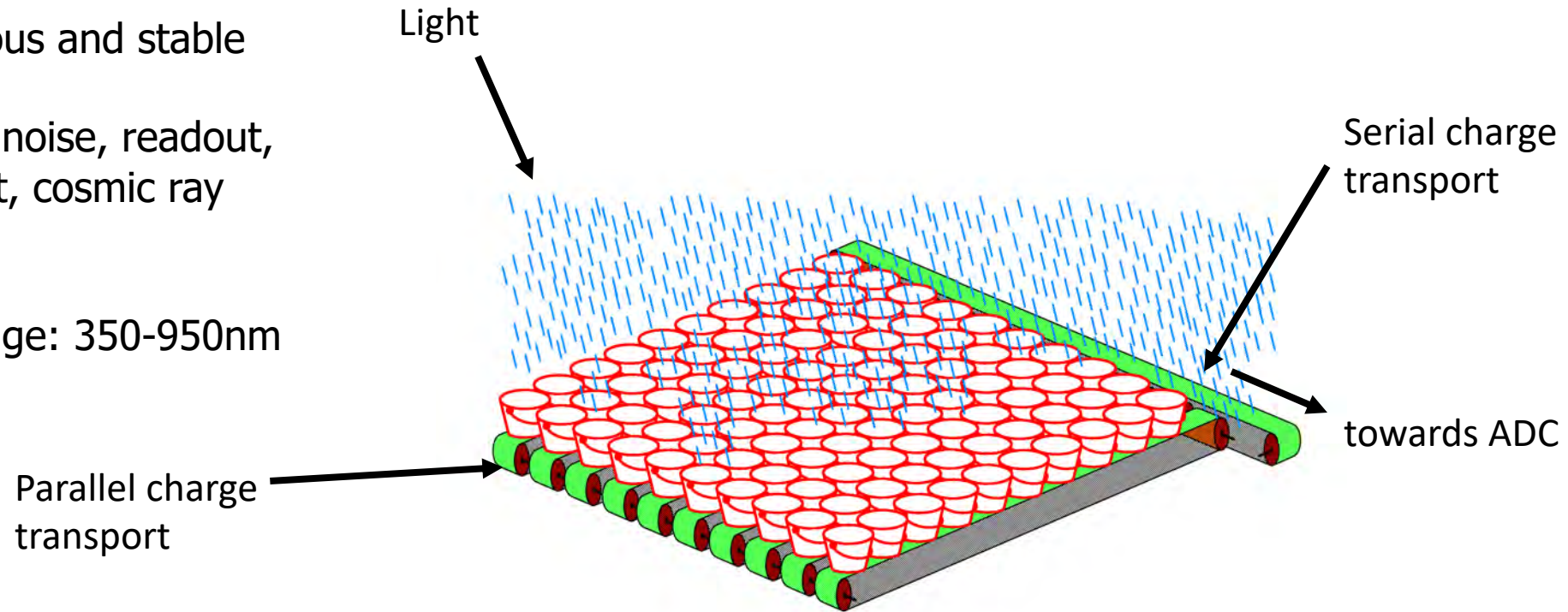
CCD properties:

High QE (up to 98%)

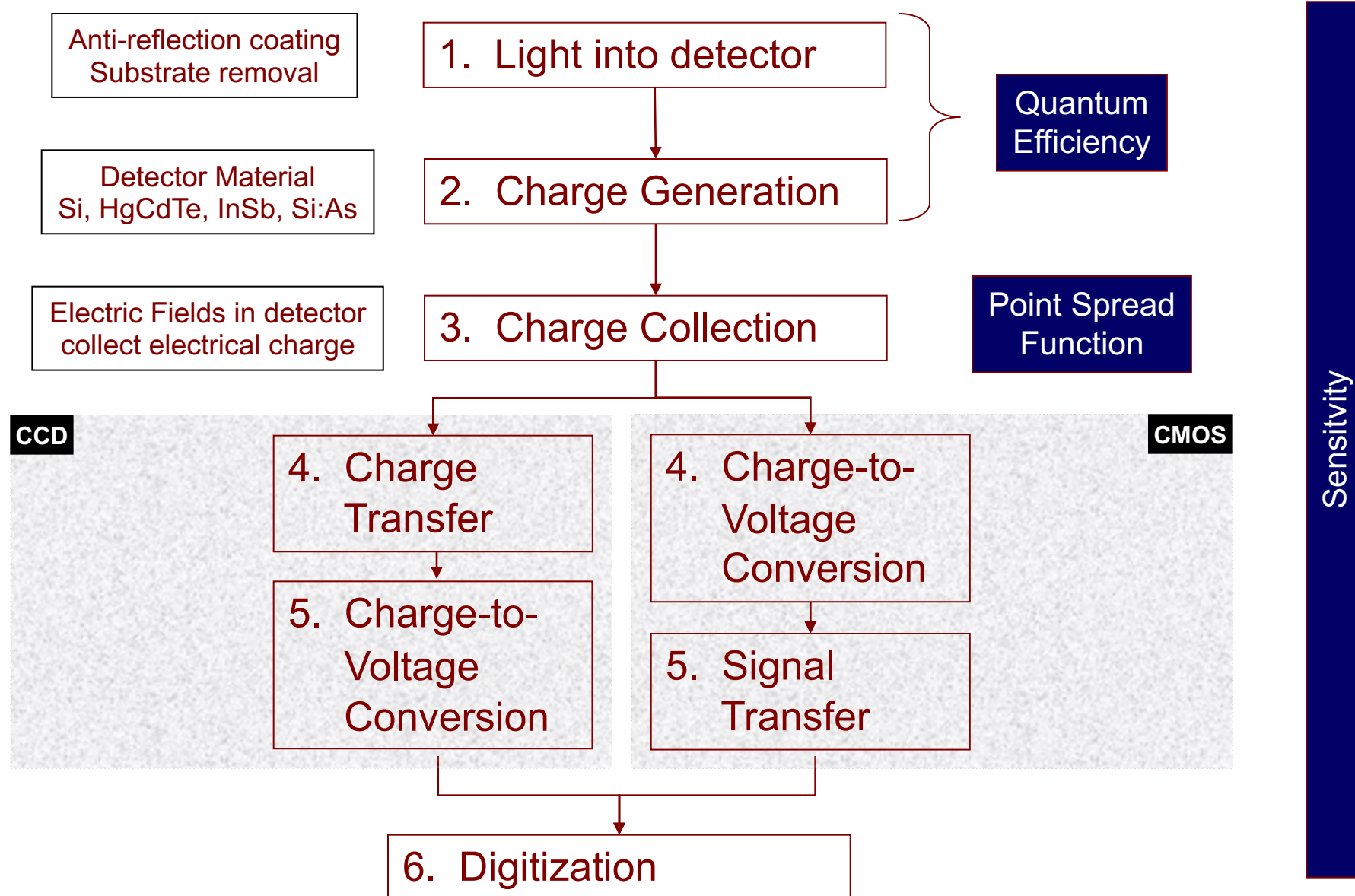
Homogeneous and stable

Noise: shot noise, readout,
dark current, cosmic ray
hits.

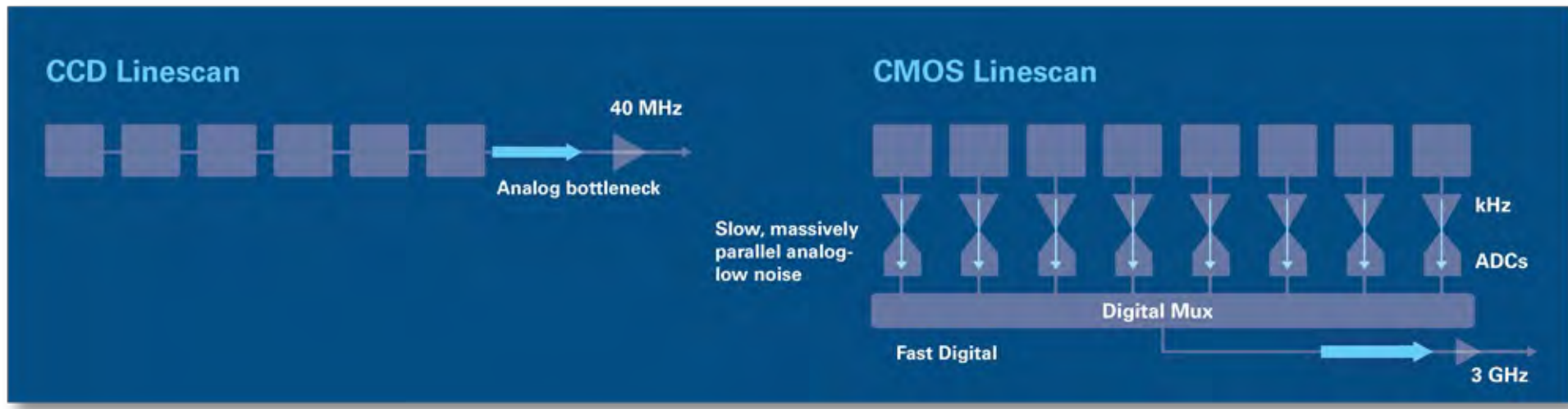
Spectral range: 350-950nm



6 steps of optical / IR photon detection



Converting photoelectrons to numbers

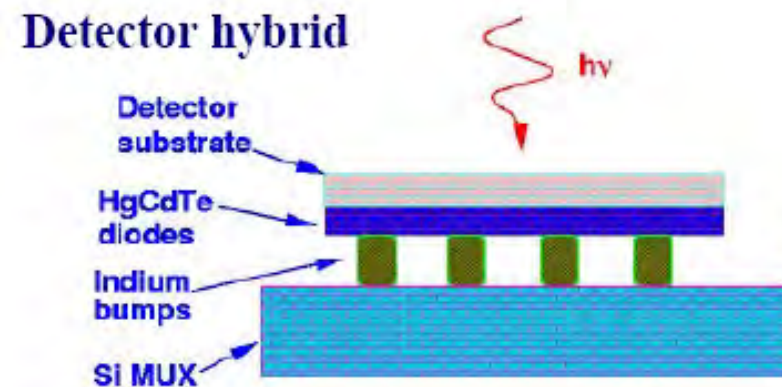
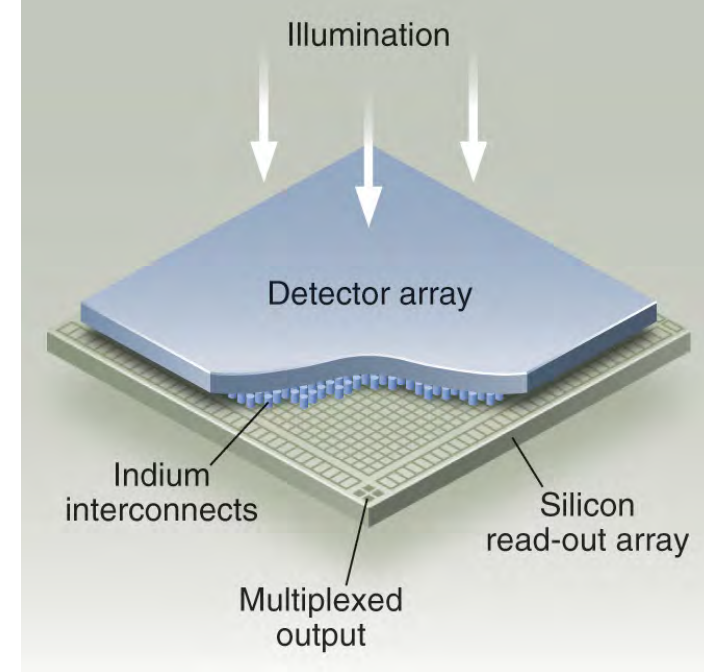


Courtesy Jim Beletic, Teledyne

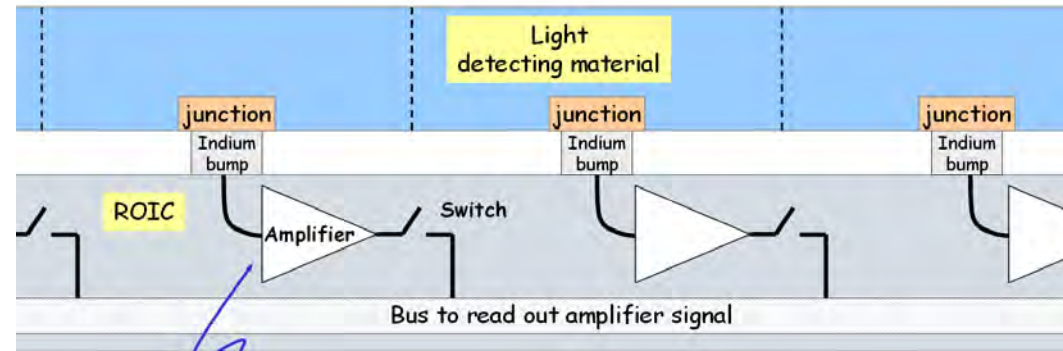
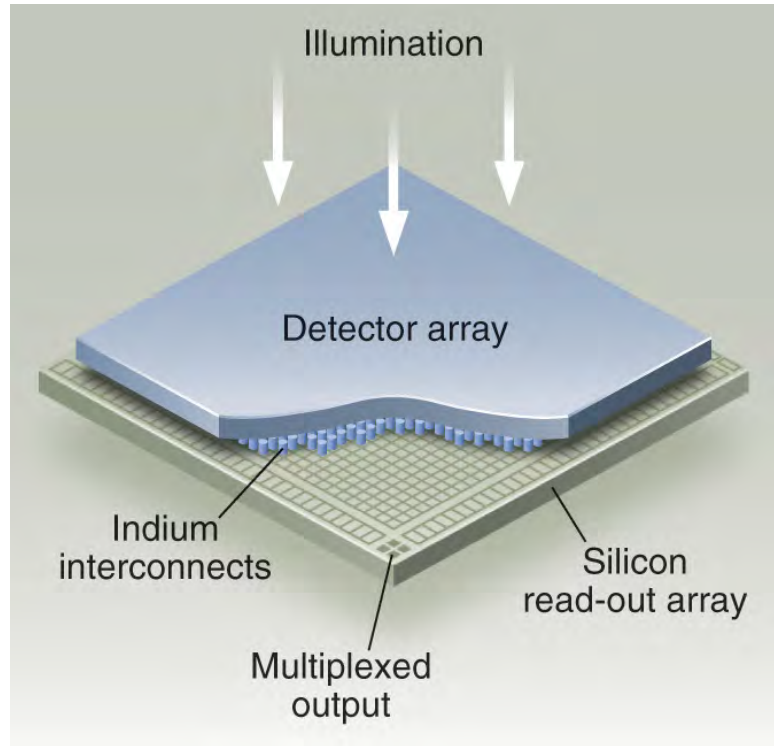
- CCDs are more homogeneous but have slow readout
- CMOS are much faster but different amplifiers and ADCs are harder to calibrate

Infrared detectors

- IR detectors are hybrid CMOS devices.
- Light-sensitive layer is made of special material (e.g. HgCdTe or InSb) sensitive up to required λ .
- Silicon electronics is well developed, therefore amplifiers and multiplexor are made in silicon.
- Working temperatures: 10-60 K, thermal expansion problem.



Hybrid detector architecture

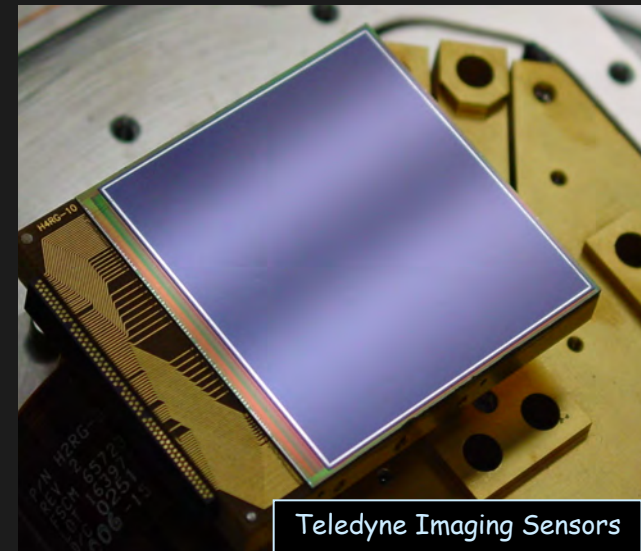
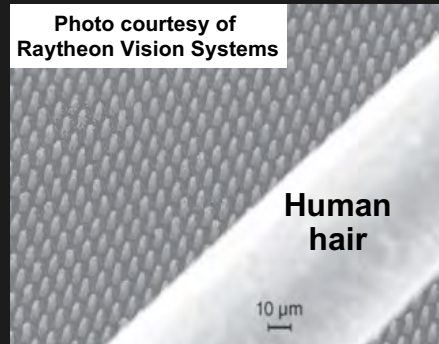


This amplifier contains one or more MOSFETs
MOSFET = metal oxide semiconductor field effect transistor

Mature interconnect technique:

- Over 16,000,000 indium bumps per Sensor Chip Assembly (SCA) demonstrated
- >99.9% interconnect yield

Photo courtesy of
Raytheon Vision Systems



Detector comparison

CCD:

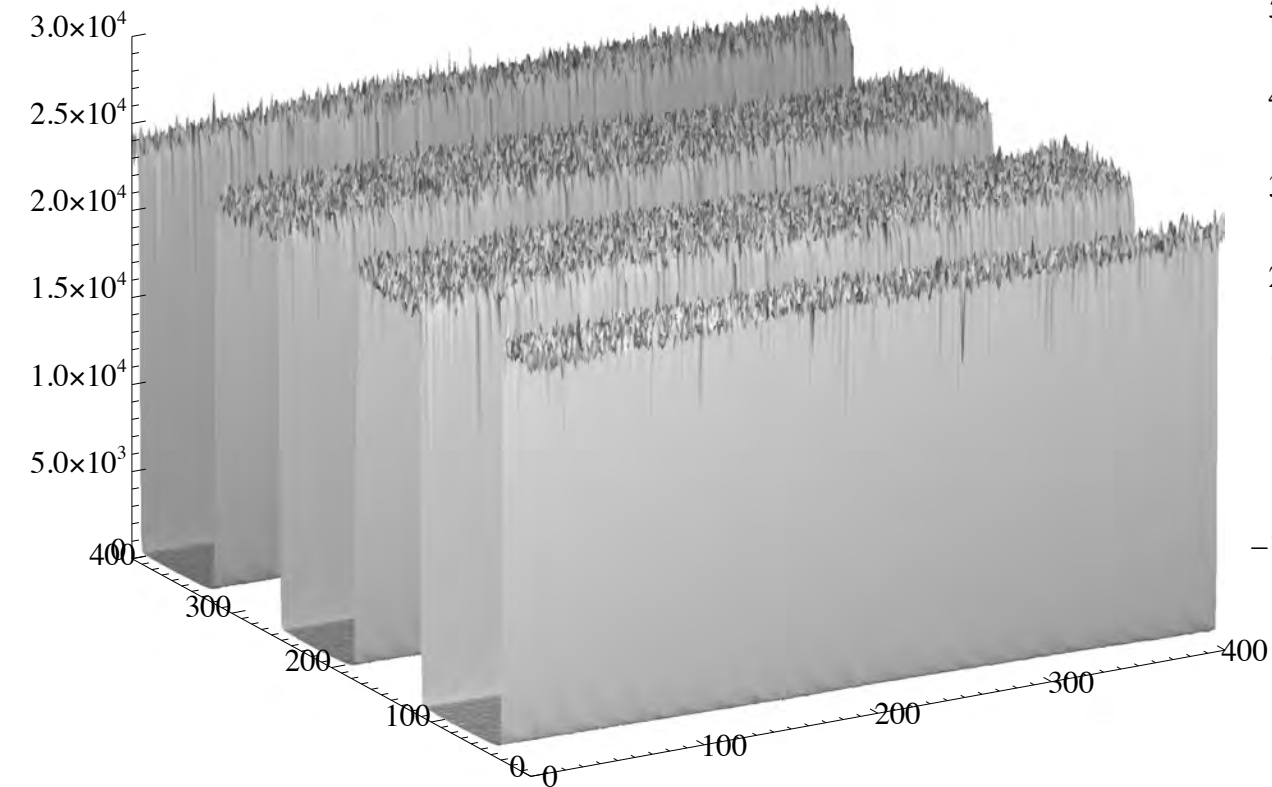
- High QE, more homogeneous, low dark current, nearly perfect cosmetics.
- Slow, limited wavelength range, sensitive to cosmic ray hits (limits exposure time).

Hybrid CMOS:

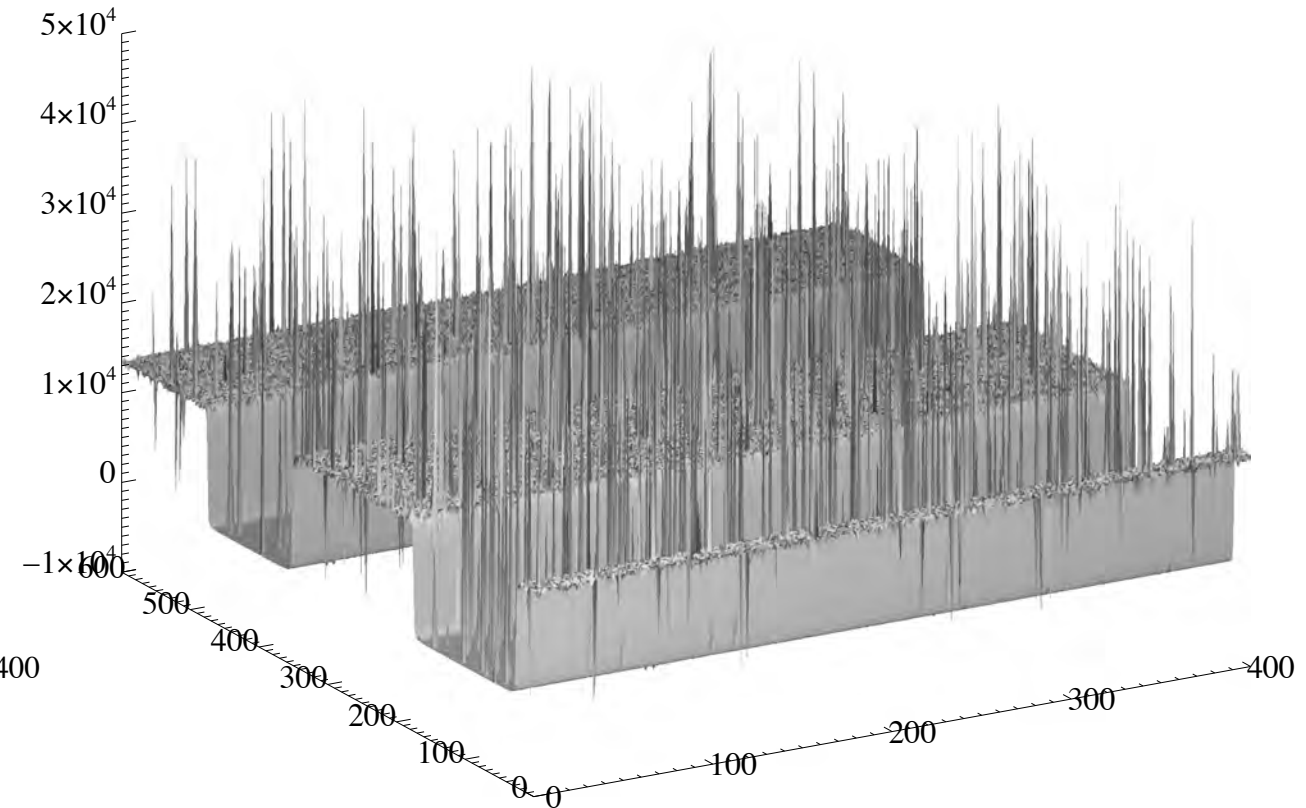
- Fast, non-destructive readout reduces cosmic ray impact, spectral range on demand.
- Terrible cosmetics, higher dark current, inhomogeneous.

Flat field image comparison



ESO UVES CCD



CRIRES+ Hawaii 2RG CMOS

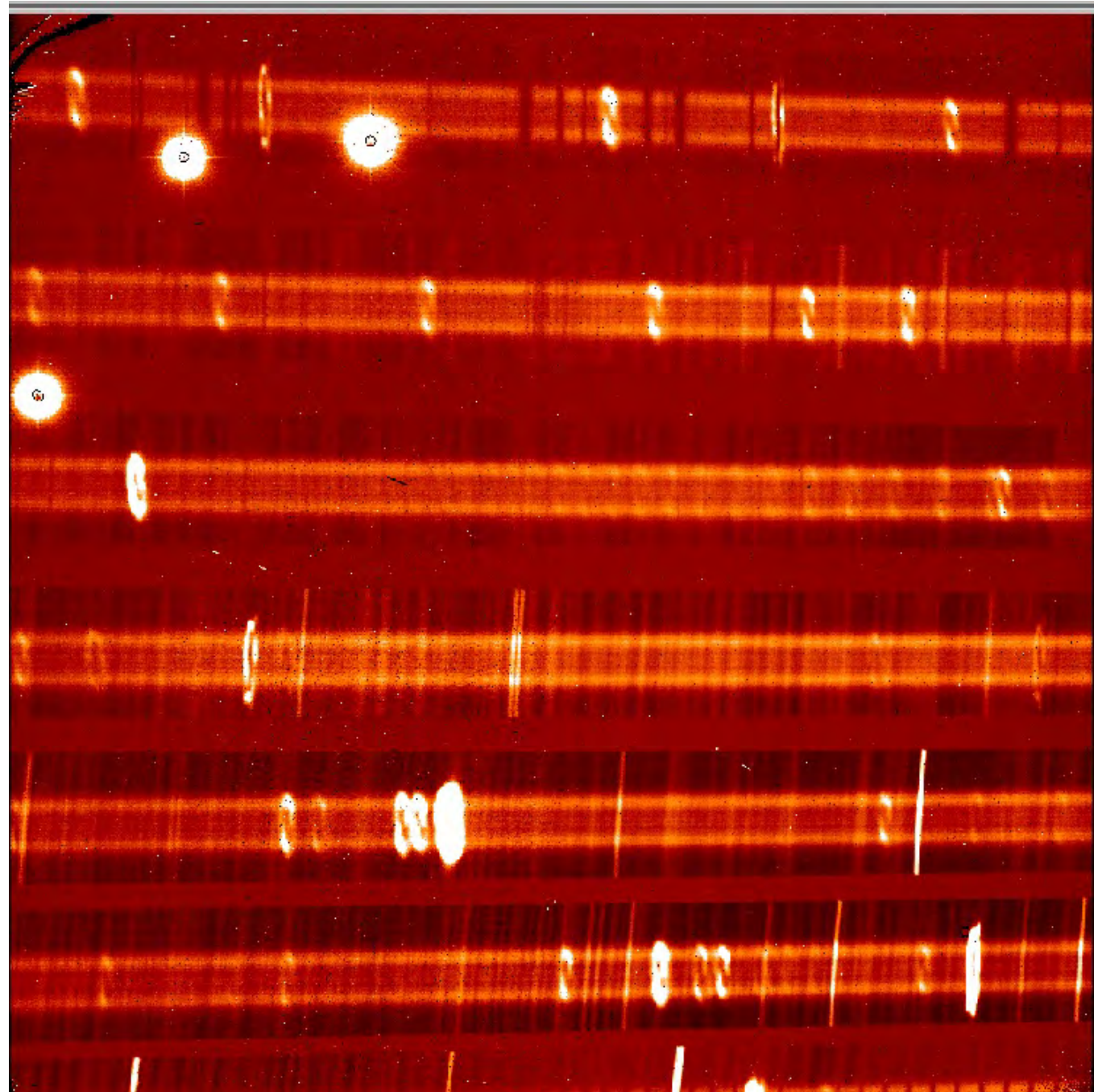


Part 3: What is a slit?

- Traditional slit  offers some spatial information. It can be useful for extended sources but even for point sources it can help subtracting sky background. SPATIAL INFORMATION!
- If you are focussed on point sources then a “slit” can be a hole  or the entrance to an optical fiber. You lose the spatial information but (with a few tricks) you gain stability on the spectrometer side because you can (a) put spectrometer in a controlled environment and (b) the entrance beam inside the spectrometer is not sensitive to guiding, vibrations, wind or seeing variation (only the intensity changes). HIGH STABILITY!

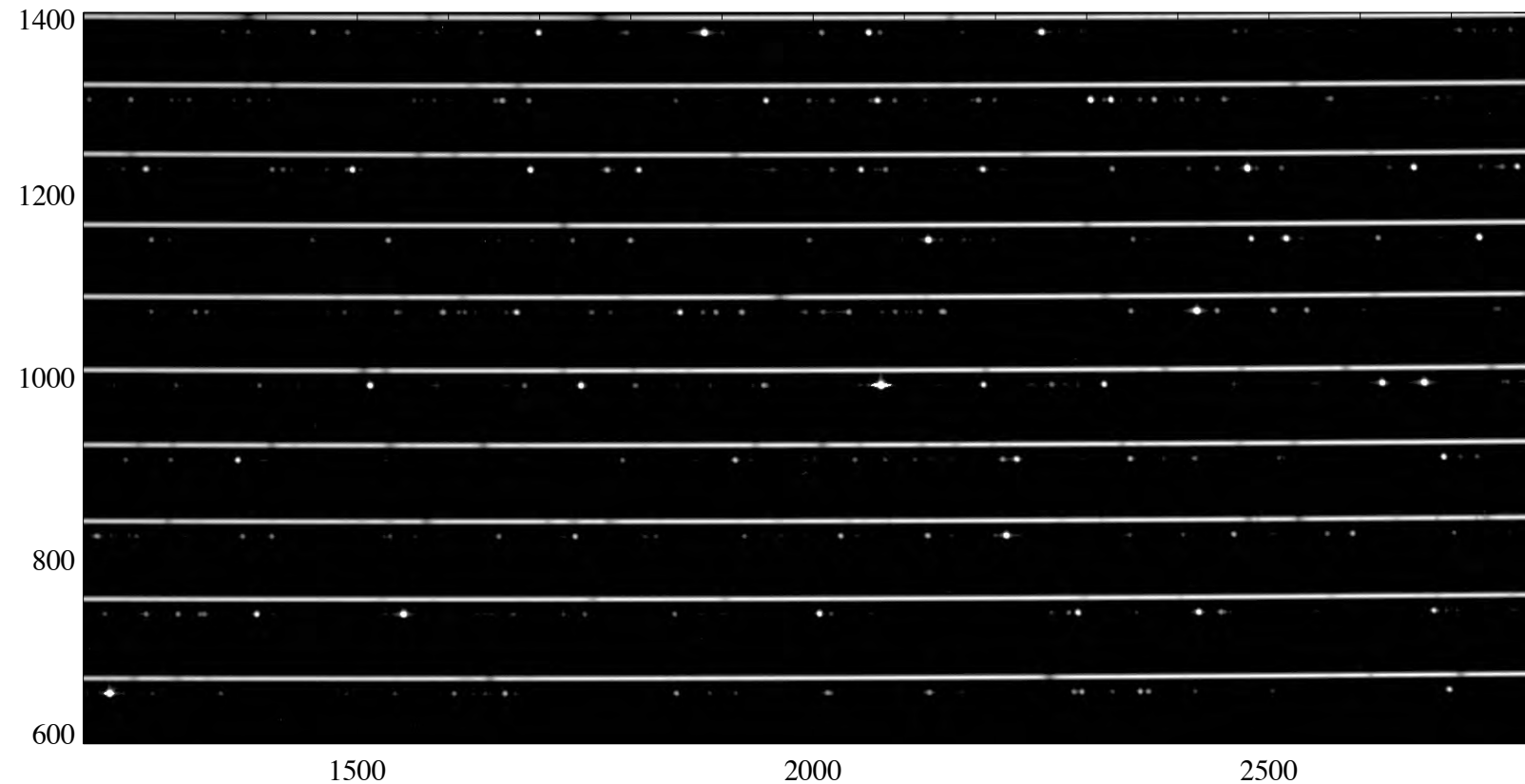
Slit spectrometer

Keck NIRSPEC (infrared, slit,
extended object)



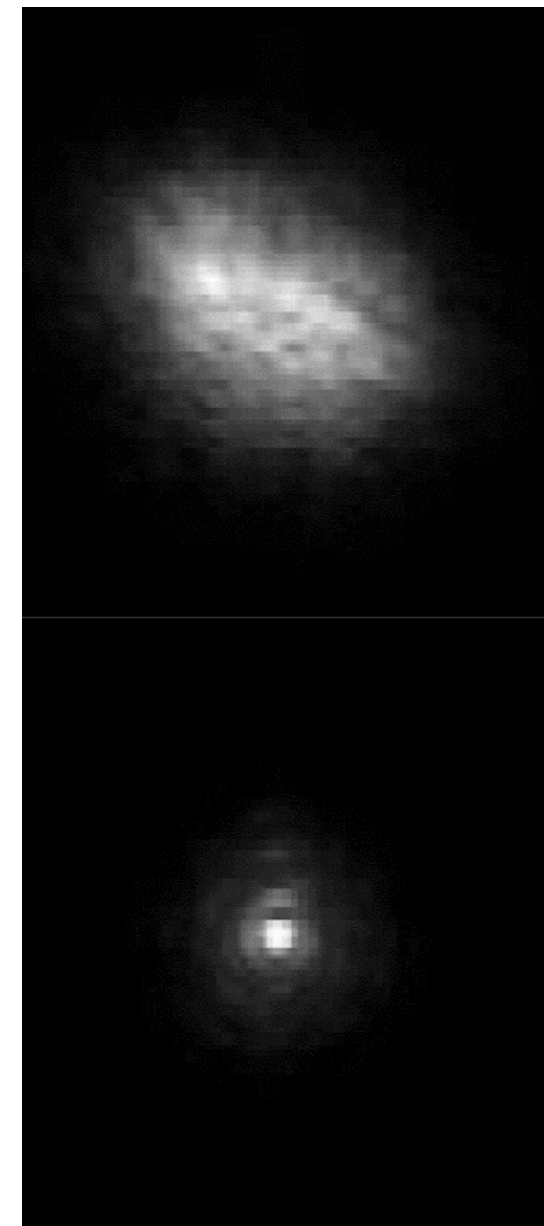
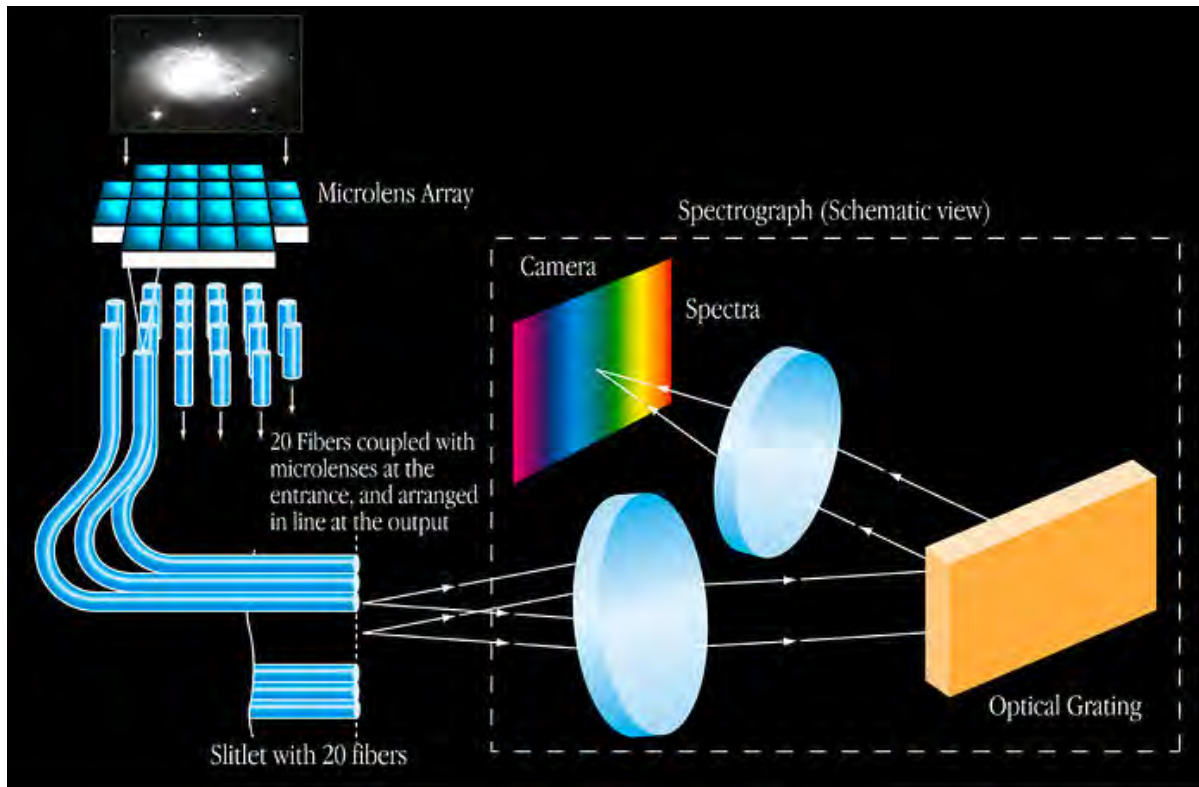
Fiber spectrometer

HARPS (optical, fiber, star+ThAr)



The best of two worlds?

Pupil slicing with microlenses and fibers

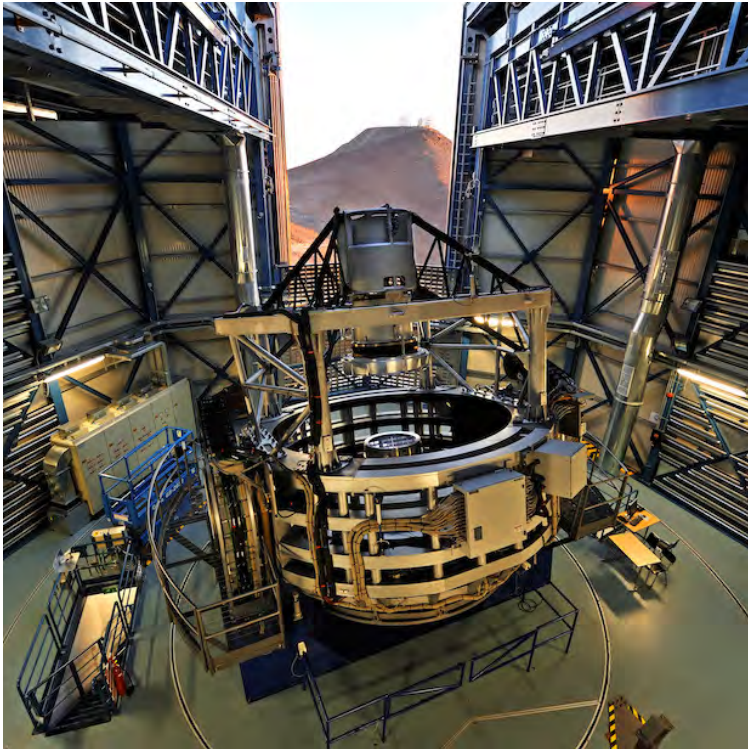


CRIFES+ adaptive optics system

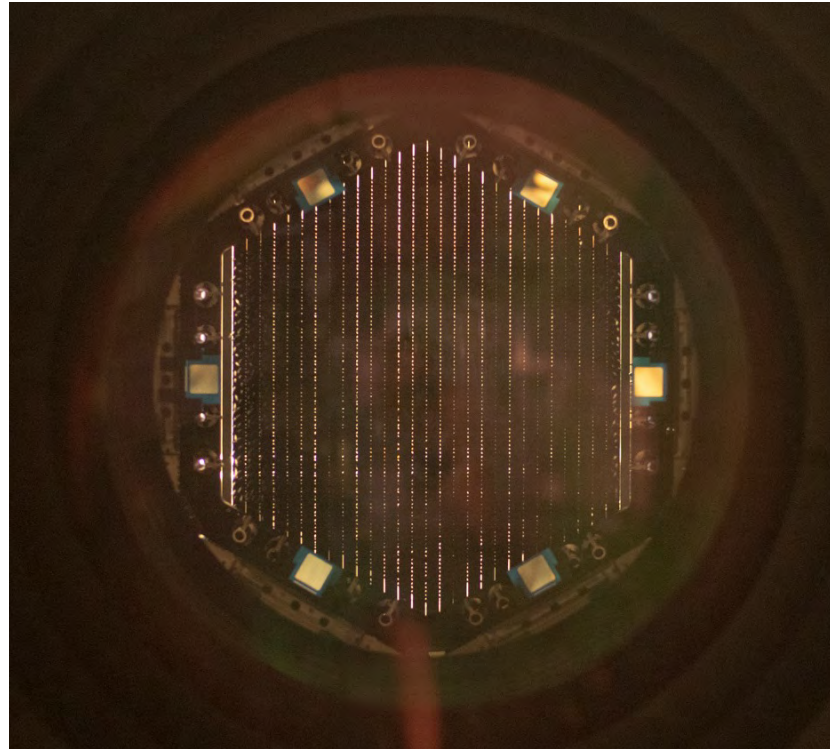
Part 4: Multiplexing

Multi-fiber 4MOST (4m VISTA telescope, Paranal, 2400+ fibers!)

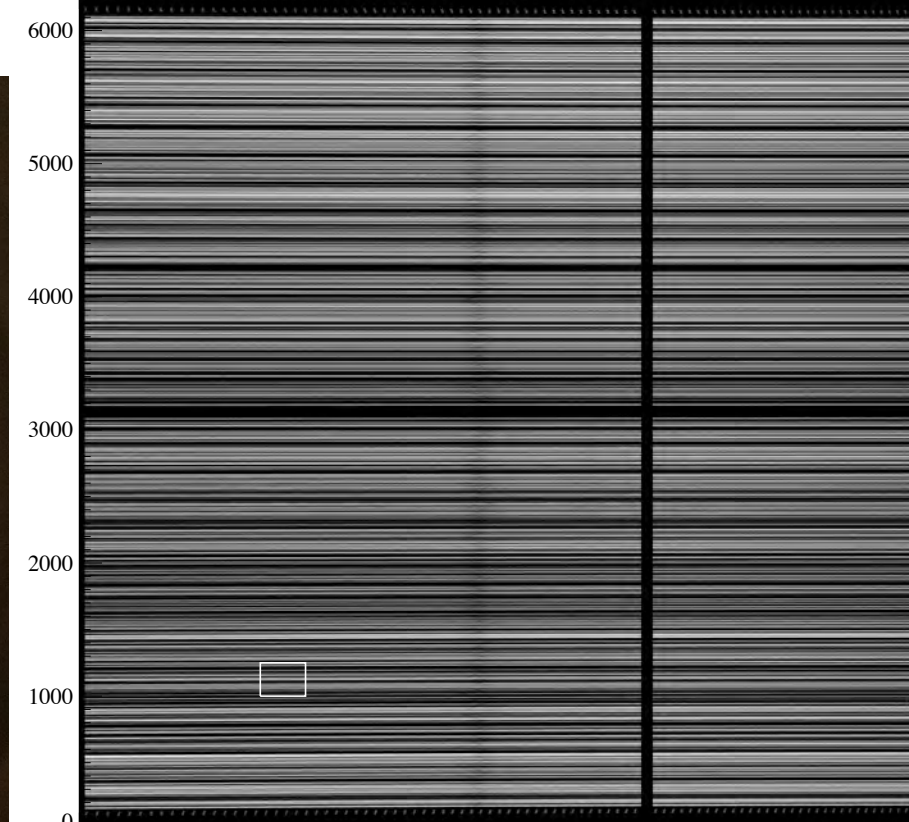
Telescope



Focal plane: fiber positioner



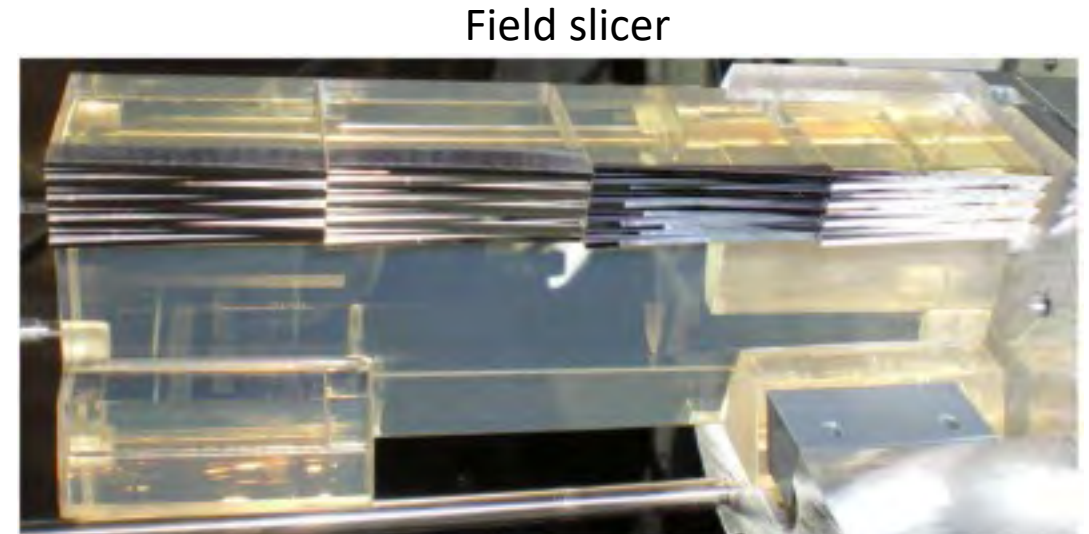
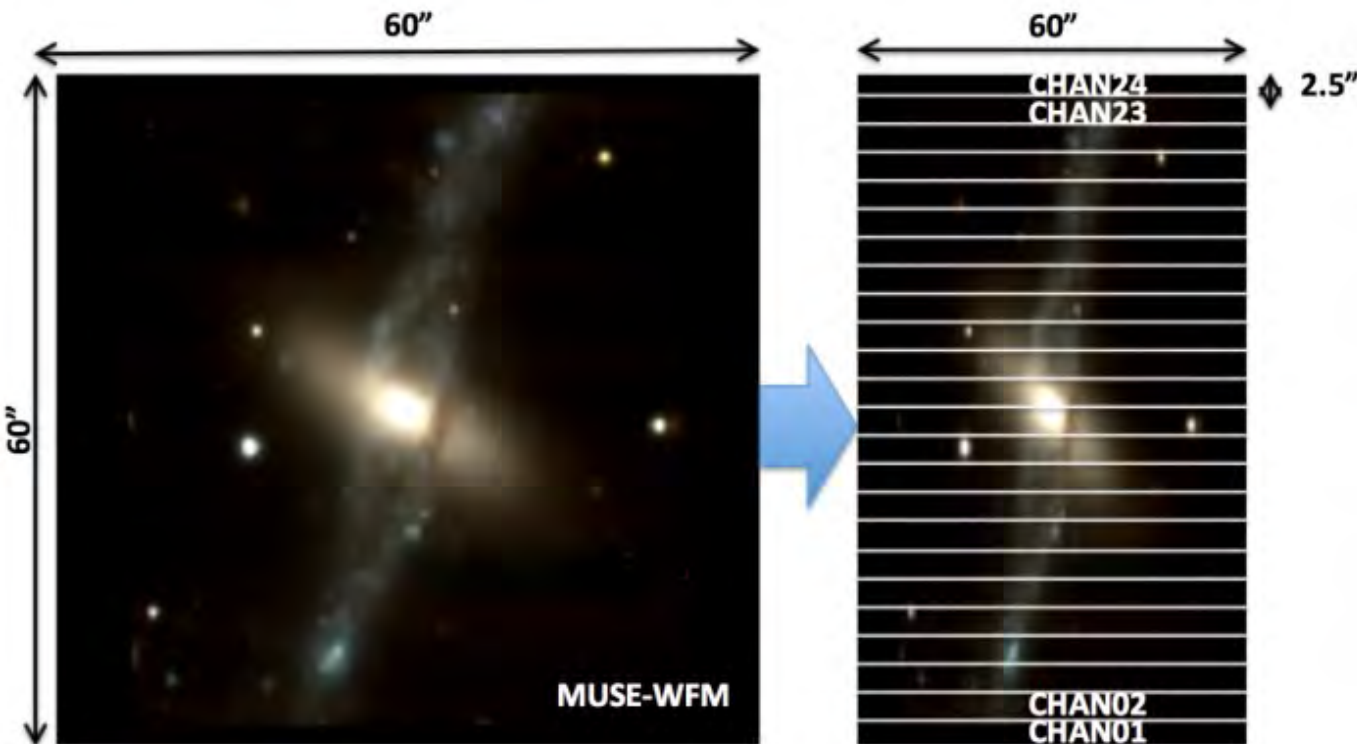
Fragment of the focal plane



Integral Field Unit (IFU)

ESO MUSE (Multi Unit Spectral Explorer)

1 arcmin² or 7.5 arcsec² are divided into 24 fields and each is sliced in 48 strips acting as slits for 24 medium resolution spectrometers.



MUSE in practice

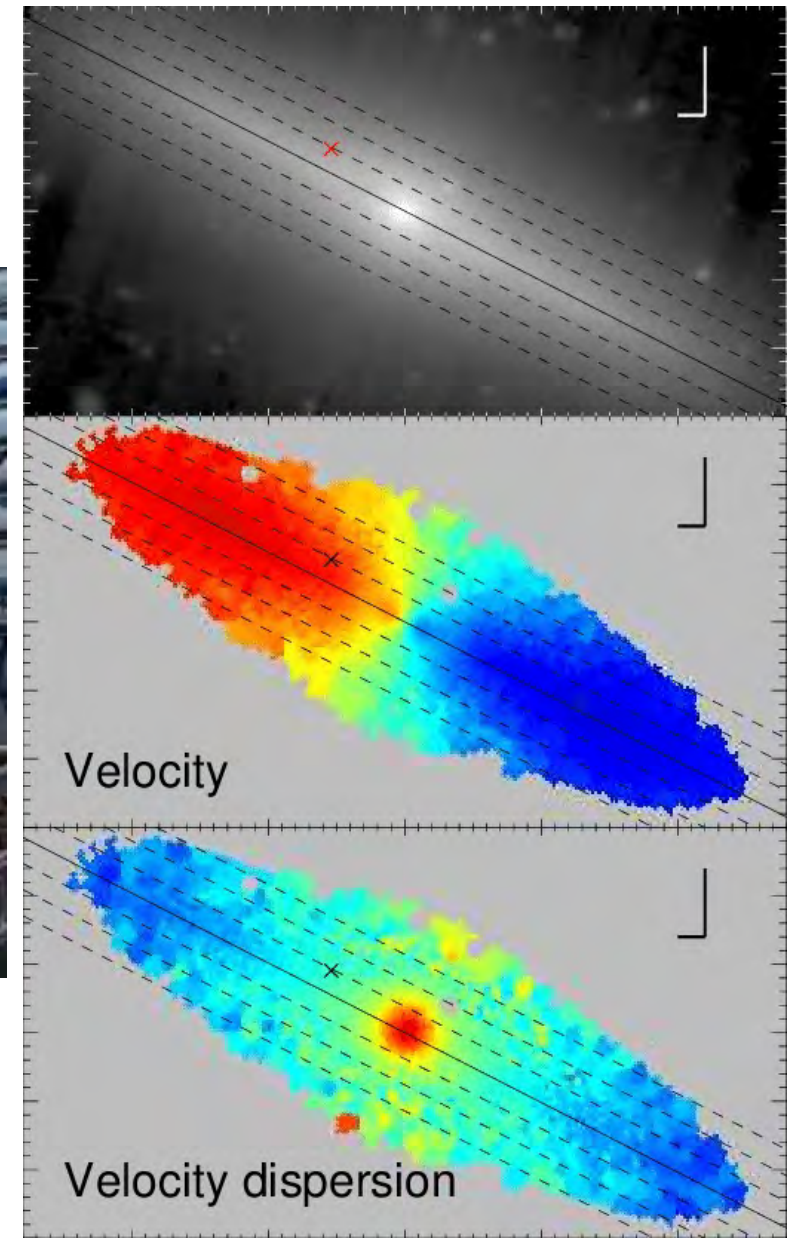
ESO VLT UT4



MUSE on Nasmyth platform



Spiral galaxy ESO 243-49 with MUSE



MUSE continued

- The result is an image cube with spaxel size of 0.2" or 0.025".
- For each spaxel one get a spectrum covering 465 to 930 nm with variable R from 1750 to 3750.
- MUSE is supported with laser guide star AO facility that can correct and stabilize 1 arcmin² field of view.
- This is a great tool to study dynamics of galaxies, groups of galaxies, star clusters, streams, solar system objects etc.

Exposure Time Calculator

- Today every instrument on major telescopes has a simulator called ETC.
- An ETC is based on a physical model of an instrument calibrated on real data.
- An ETC allows you to get S/N for a given setting, target and exposure time or estimate the exposure time given S/N.
- ETCs are getting more realistic and versatile and the use of ETC is often required for an application for observing time.

Data Reduction Software

- Nowadays, when instrument price is well above 5 M€ (and well above 50 M€ for the ELT) more attention is given to the DRS.
- It now models the raw data given the PSF and the spectrum maximizing the S/N.
- The DRS is not a black box. It has a few tunable parameters. What is run by the observatory is done with default values and the results can often be improved by careful tuning of parameters.
- Examples are “detection” using low S/N data, handling detector defects, background subtraction, wavelength corrections etc.

Conclusions (1/2): Why am I telling you all this?

- The instruments I described are just examples of what is available to the astronomical community.
- How to choose?
- Some instruments require infrastructure: 4MOST works best as a survey machine and so preparing/joining a survey is the best strategy.
- Some amazing capabilities require compromises. MUSE has a limited spectral resolution, ESPRESSO only works on point sources, etc.

Conclusions (2/2): How to use this in a best way?

- Think what is the most crucial property needed for your project to succeed.
- Look at publications done with a given instrument data.
- Look at the manual of the instrument.
- Use the ETC.
- Study the archival data.
- Check the DRS manual, decide if the pipeline-reduced data is good enough or you need to install the DRS locally and play with parameters.
- Consider alternative facilities.